

INVESTIGATION ON VELVET HAND ILLUSION USING PSYCHOPHYSICS AND FEM ANALYSIS

M. Ohka¹, Y. Kawabe¹, A. Chami¹, R. Nader¹, H. B. Yussof², and T. Miyaoka³

¹Graduate School of Information Science, Nagoya University,
Furo-cho, Chikusa-ku, 464-8601, Nagoya, Japan, ohka@is.nagoya-u.ac.jp

²Faculty of Mechanical Engineering, Univesiti Teknologi MARA
Shah Alam, Selangor Darul Ehsan, 40450, Malaysia

³Faculty of Comprehensive Informatics, Shizuoka Institute of Science and Technology
2200-2, Toyosawa, Fukuroi, 437-8555, Japan

Abstract-In the velvet hand illusion (VHI), a person rubs his/her hands together on either side of wires strung through a frame, producing the sensation of rubbing a very smooth and soft surface like velvet. We investigate the VHI mechanism to obtain an effective hint for a new tactile display because such tactile illusions play a good role in deceiving the brain so that operators believe that a virtual sensation is real. To elucidate the VHI mechanism, we propose two approaches: one uses psychophysics to obtain human mental models; the other is a finite element method (FEM) to evaluate the tactile stimulus that causes VHI. Based on psychophysical experiments using Thurstone's Paired Comparison, VHI strength depends on the distance between two adjacent wires, and VHI caused by wide spacing of wires is considerably stronger than that caused by narrow spacing. In FEM analysis, a mesh model of fingertips is produced to mimic an actual finger to evaluate the strain energy density (SED) because one mechanoreceptive unit is a slowly adaptive mechanoreceptive type I unit (SAI) that well responds to SED. There is a considerable difference between the SEDs of the one-finger case and the two-finger case (VHI case): the peak SED value for the VHI case is around half of that for the one-finger case. The VHI mechanism is assumed as follows: although the area bounded by two wires moves relative to the hands, tangential force does not occur on the hand surface except for the wire-passing portion, causing operators to experience the illusion of touching a smooth virtual film with a zero coefficient of friction. Since VHI decreases with a decrease of wire spacing and an increase of the peak value of SED, excessive temporal stimulus generated by wire prevents VHI from increasing.

Index terms: Tactile display and sensor, Illusion, Psychophysics, Velvet hand, Paired comparison, Finite element method, Strain energy density

I. INTRODUCTION

In virtual reality, there are many kinds of experimental tactile displays such as mechanical vibratory pin arrays [1], surface acoustic waves [2], pin arrays driven by pneumatic actuators [3] and piezoelectric actuator arrays [4]; however, all of these generate pressure distribution to emulate the tactile sensation of an operator's fingers touching a virtual object. Since the tactile display does not generate relative motion between the finger surface and the display pad, the operator cannot feel a real sense of touching. If our brain believes the virtual object to be a real object in spite of no relative motion on the tactile display, we can improve the above ordinal tactile displays. In this paper, we adopt a tactile illusion to trick an operator's brain into believing the operator is touching a real object.

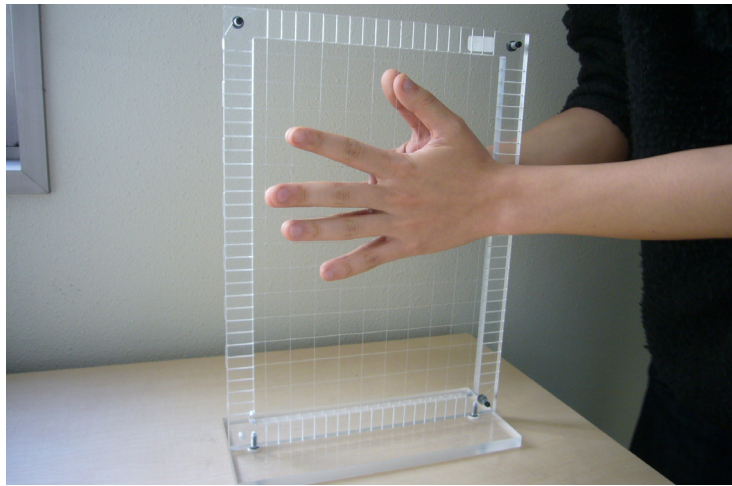


Figure 1. Wire mesh generating velvet hand illusion

There are several tactile illusions such as the velvet hand illusion (VHI) [5], fishbone and comb illusions [6]. Since the velvet hand illusion causes the sensation of contacting a given material, i.e. velvet (material-feeling, hereafter), we concentrate on this illusion and apply it to a new tactile display design. VHI is caused by such a wire mesh, as shown in Fig. 1. A person rubs his/her hands together on either side of wires strung through a frame, producing the sensation of rubbing a very smooth and soft texture like velvet. This tactile illusion is caused by brain activity. In another report, we began to study a tactile display utilizing the comb illusion to emulate relative motion between a tactile display and a finger surface [7]. Since we focus on VHI, which has the

possibility to generate material-feeling, this study, in combination with the above study, we will introduce guidelines for a new tactile display.

In this paper, we propose two approaches: one uses psychophysics to obtain human mental models; the other is the finite element method (FEM) to evaluate tactile stimuli that cause VHI. For the psychophysical experiments, we developed equipment composed of a pair of parallel wires and a frame because VHI is caused not only by a wire mesh but also by two parallel wires. We prepared five sets of equipment with different distances between the two wires to obtain the optimum distance for causing maximum VHI. In the active touch condition, human subjects bring their hands together on opposite sides of the two wires and move them to feel VHI. To compare the active touch condition with the passive touch, the equipment is put on a motorized x-table and moved with reciprocating motion to cause the subject to passively feel VHI. Based on experiments using Thurstone's Paired Comparison [8], we evaluated variation in VHI strength with different distances between two adjacent wires and the difference between passive and active touch in VHI.

In the latter approach using FEM analysis, a mesh model of a fingertip is produced to mimic an actual finger to evaluate strain energy density (SED) because one of the mechanoreceptive units is a slowly adaptive mechanoreceptive type I unit (SA I) that well responds to SED [9]-[11]. The mesh model of a fingertip has a bone, a nail, and three-layered skin composed of dermis, epidermis, and subcutaneous tissue. The modeled dermis has papillae in its inside because the SA I receptors are aligned along the papilla ridge to enhance the sensitivity of the SA I receptor due to the strain concentration. Since the FEM calculation results are compared to the psychophysical experimental results, the two-finger mesh models sandwiched the two wires and moved along a plane formed by the two centers of wire. To compare the VHI occurring case with the no occurring case, a numerical simulation was performed with a one-finger mesh model, which moved along the plane formed by two wires.

Finally, we elucidated the VHI mechanism on the basis of the above psychophysical experiments and FEM analysis. After we specified the condition for VHI arising obtained from the psychophysical experiment, we examined the stimulus provided to the SA I receptor when VHI arises.

II. BASIC CHARACTERISTICS OF VHI

Mochiyama et al. examined VHI and obtained the following conclusions [6]:

- 1) A virtual plane is perceptible from wire.
- 2) A smooth and comfortable sensation is perceived as if the opposite hand was not the operator's hand.
- 3) Both hands are not always required to be from the same person; the other hand must be moved synchronously with the other hand.
- 4) VHI is caused regardless of the movement, including active or passive touch.
- 5) On the basis of observation using functional Magnetic Resonance Imaging (fMRI), it is assumed that a virtual plane between the hands is formed from two edges by a filling-in filter in the brain.

To elucidate the VHI mechanism, we examined the relationship between illusion intensity and the configuration of the mesh wire using a series of psychophysical experiments, in addition to the items listed above. Additionally, we examined the stimulus condition for SA I receptors using FEM analysis, which can estimate the nerve signal of SAI receptors instead of directly obtaining nerve signals using a tungsten probe.

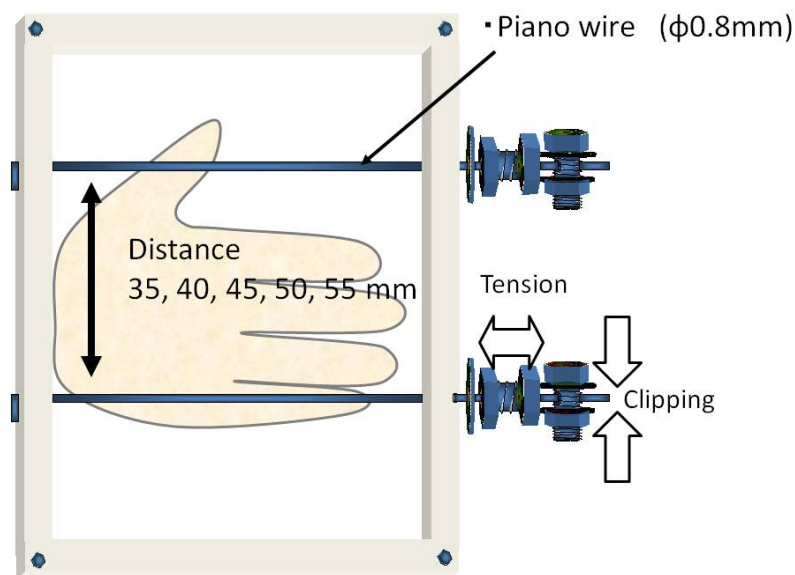


Figure 2. Frame equipped with two wires for VHI experiment

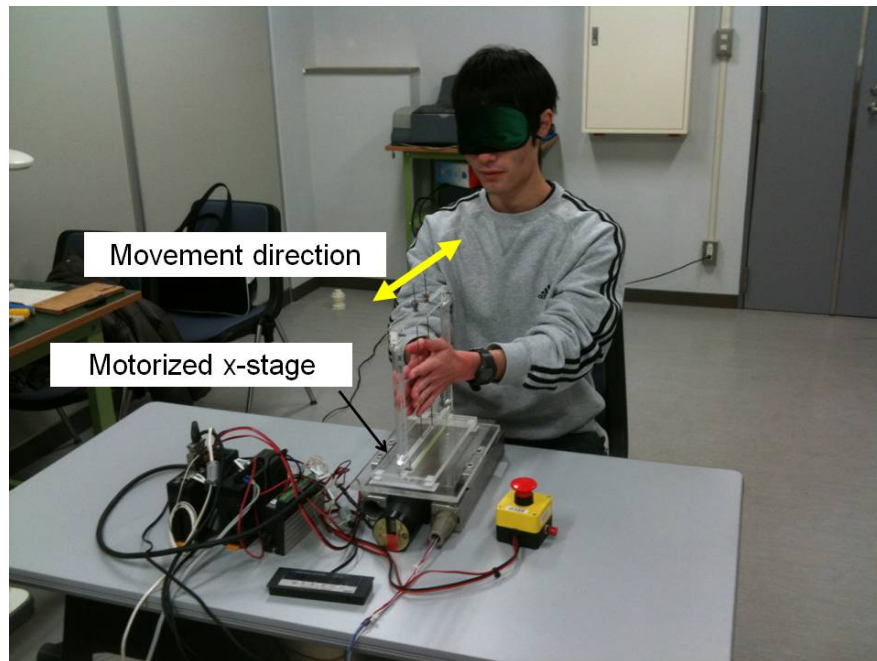


Figure 3. Scene of experiment in passive touch test

III. PSYCHOPHYSICAL EXPERIMENTS

a. Experimental Apparatus

To examine VHI, we have produced several kinds of wire mesh equipment with different mesh intervals. One of them is shown in Fig. 2. The frame is made of acrylic board; two piano wires 0.8 mm in diameter are strung through the frame. Since VHI intensity seems to depend on tension of the wire, the piano wire was strung with sufficient tension using a bolt and a nut.

In the active touch test, the equipment is fixed on a table and human subjects bring their hands together on opposite sides of the two wires and move their hands. In the passive touch test, the equipment is fixed on a motorized x-table and is moved with reciprocating motion, while the subjects do not move their hands, as shown in Fig. 3.

b. Experimental Procedure

In this experiment, we aimed to obtain an optimum distance between two wires (wire spacing) for VHI using Thurstone's Paired Comparison [8]. As stimuli, we presented human subjects with five wire spacings: 35, 40, 45, 50 and 55 mm. A separate piece of equipment (set-up) was produced for each spacing; pairs were produced from the five set-ups. In each trial, subjects touched two different set-ups using the thenar part of the hand, and chose the set-up that generated stronger

velvet feeling. To control motion speed, human subjects moved their hands in time with a metronome (1 sound/sec). Since a stroke of hand motion was around 60 mm, the hand-motion speed was almost 120 mm/sec.

The above trial was performed for every pair to determine which set-up generates the strongest velvet feeling. Human subjects were eight persons in their twenties; all experiments were performed at a room temperature of 24° C; all human subjects wore an eye-mask. Every subject reported that VHI was caused by two hands touching, not by one hand alone.

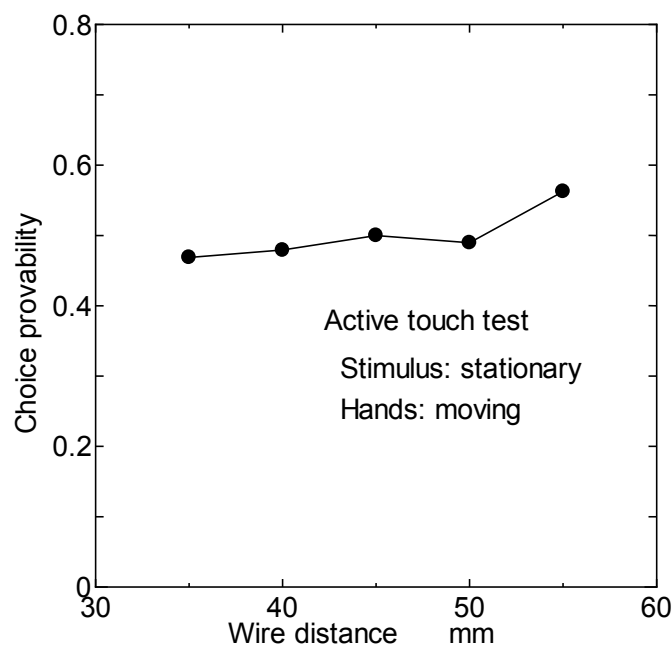


Figure 4. Average of VHI strength in active touch test

c. Experimental Results of Active Touch Test

First, we examine the result of the active touch test. If the effect of wire spacing on intensity is examined according to the average of all subjects' answers, a flat curve that has slight inclination is obtained as shown in Fig. 4. Since this result provides no optimum condition for VHI, we investigated the individual responses of each subject and found that they could be divided into two groups, I and II. Figs. 5(a) and (b) show experimental results for Groups I and II, respectively.

Since Group I shows a U-shaped curve, the subject feels strong VHI in both 35-mm and 55-mm wire spacing as shown in Fig. 6(a). Although 35-mm wire spacing produces strong VHI in Group

I, it is felt to be weak in Group II as shown in Fig. 6(b). On the other hand, both Groups I and II feel strong VHI in wide wire spacing of 55 mm. This indicates that there are two kinds of feeling in wide wire spacing and narrow wire spacing, and that subjects are divided into two groups according to whether they can distinguish the two feelings or not. This result implies that VHI is generated by at least two sensations. If we can control these two sensations, there is a possibility to produce several variations on VHI such as a smooth and comfortable feeling and a plane feeling.

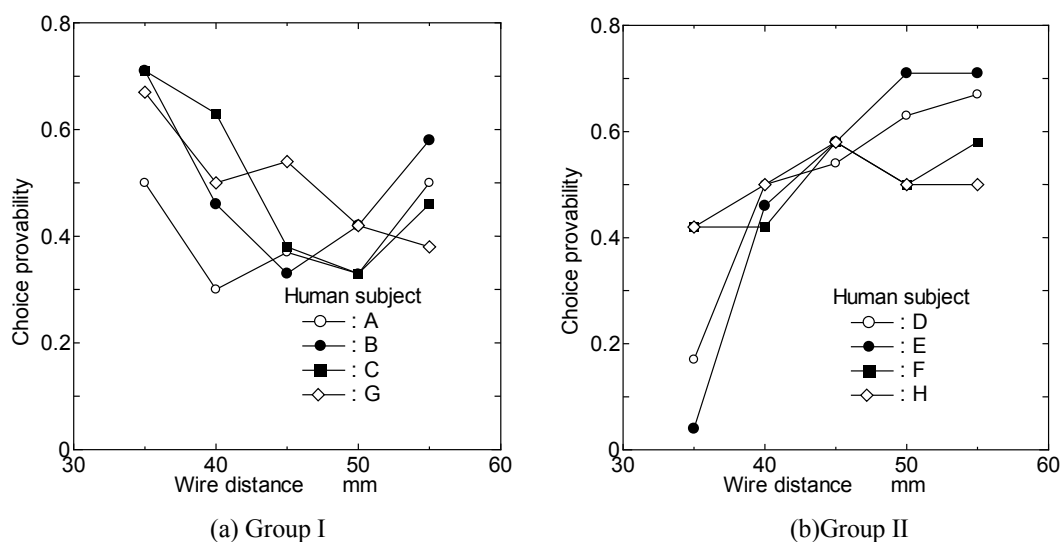


Figure 5. VHI strength for Groups I and II in active touch test

d. Comparison Between Active and Passive Touch

To compare the active touch condition with passive touch, the equipment is put on a motorized x-table and moved with reciprocating motion to make subjects feel VHI passively. Since the x-table moved with reciprocating motion (1 cyclic motion per second) and the stroke of its motion was 60 mm, the speed was around 120 mm/sec, the same as the motion speed of active touch. Compared to the case of active touch described in section A, VHI strength obtained from the passive touch test depends considerably on wire spacing as shown in Fig. 6.

According to Thurstone's Paired Comparison, we obtained the interval scale for both of active and passive touch tests to compare the passive touch result with the active touch result as shown in Figs. 7(a) and (b). Since the active touch test and the passive touch test were individually performed, the scale value obtained from each test is not compared with the other. The slope of

the regression line, however, indicates the sensitivity of VHI strength to wire spacing. The slope values of active and passive tests are 0.0122 and 0.114, respectively. Therefore, sensitivity of VHI strength on wire spacing difference caused by passive touch is nine times greater than that caused by active touch. In passive touch, VHI appears more easily.

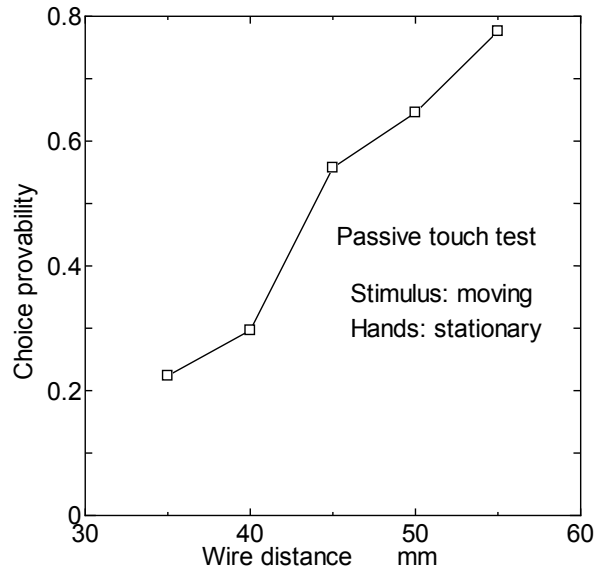


Figure 6. VHI strength for Groups I and II in active touch test

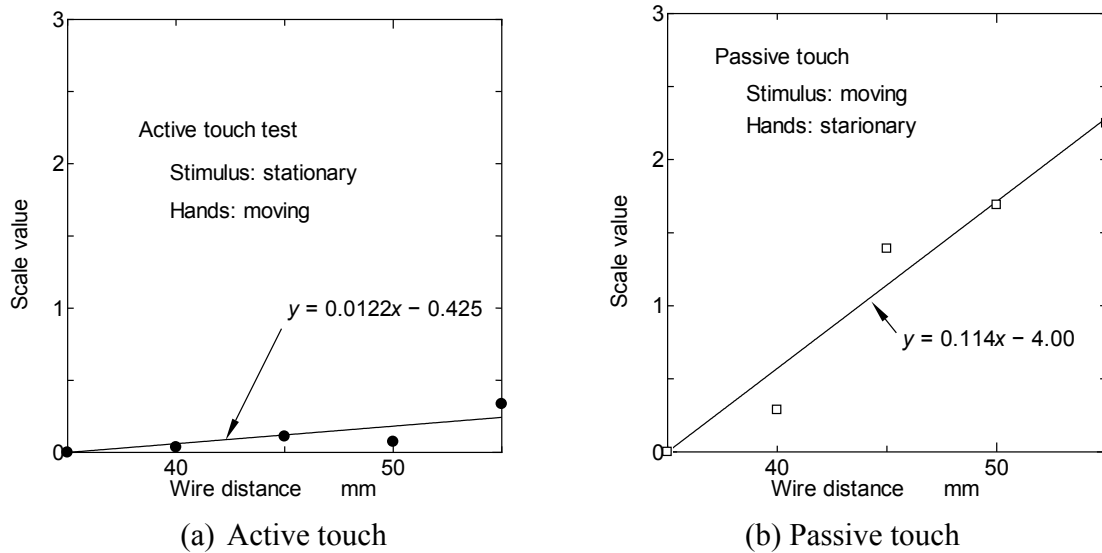


Figure 7. Variation in interval scale under active and passive touch

IV. FEM SIMULATION

a. Mesh models for FEM analysis

Figure 8 shows the intersection of an elliptical fingertip with a long 17.4-mm axis and a short 13.6-mm axis [12]. Starting from the outer one, the fingertip consists of three soft tissue layers: the dermis, the epidermis, and the subcutaneous tissue, in addition to the bone and nail. The boundary between the epidermis and dermis layers contains interference of the sinusoidal waves that are called intermediate ridges. The elements located at the tips of these ridges are considered the location of the SA I receptors, and the SEDs of these elements are considered the SA I response, as discussed before.

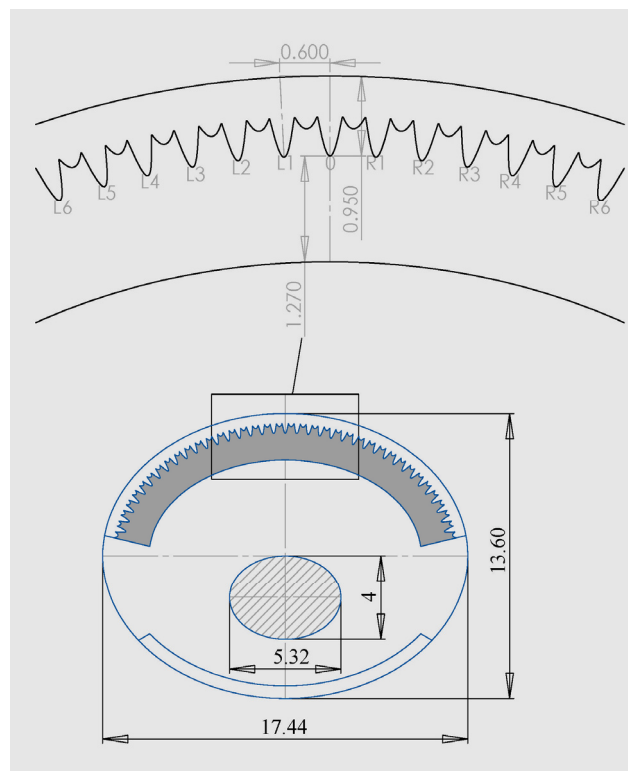


Figure 8. The geometry of the fingertip model (dimensions are in mm)

The soft tissues layers are assumed to be linearly elastic with a young modulus of 0.136 MPa for the epidermis, 0.08 MPa for the dermis, and 0.034 MPa for the subcutaneous tissue. Poisson's ratio of every material is assumed to be 0.48 [12]. Both the bone and the nail are assumed to be rigid. The model contains approximately 17,300 elements and 46,800 nodes. The simulation was performed by ANSYS Academic Release 12.0.1.

b. Simulation Procedure of VHI

VHI is caused by the following condition: 1) using two hands; 2) the presence of at least two parallel wires either parallel or perpendicular to the fingers, and 3) rubbing the hands against the wires. We examined the SA I receptor response alone by simulating a simple version of VHI on just two opposed fingers (VHI case) and compared it with the case of a finger touching the wires (one-finger case).

1) VHI case simulation starts by pressing the finger against a rigid plane with a displacement of 0.5 mm to account for the opposed finger effect (Figs. 9(a) and (b)) Then the wires ($D = 0.8$ mm and simulated as rigid bodies), whose centers are aligned with the fingertip surface, move horizontally at 21 mm/sec and deform the already pressed finger. The friction coefficient between the wires and the fingertip surface is 0.3. We used three wires with a 5-mm pitch. The boundary condition constrains the two nodes near the middle of the nail in both the X and Y directions.

2) One-finger case simulation: This case has no compression because we assume no opposing finger. The three wires have 0.5-mm centers vertically from the top of the fingertip surface (Fig. 10). This simulation insures a difference between the two cases. The other parameters are the same as the VHI case.

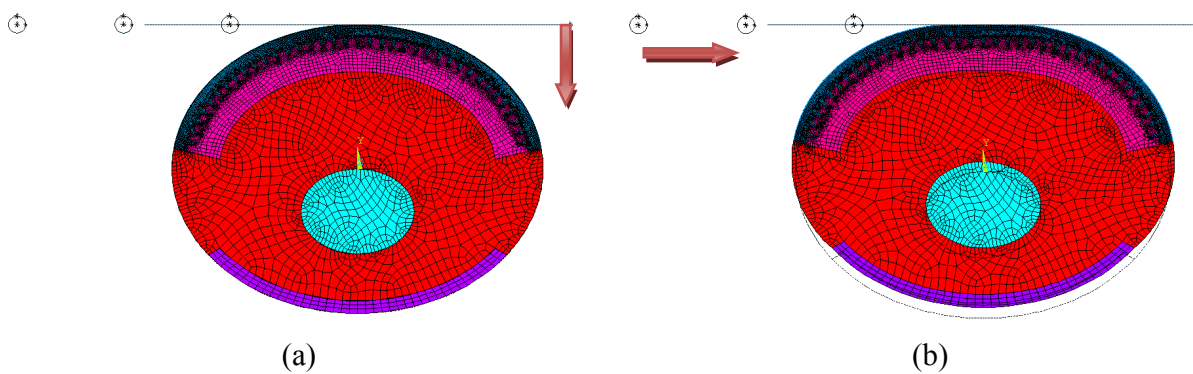


Figure 9. Simulation procedure for VHI case

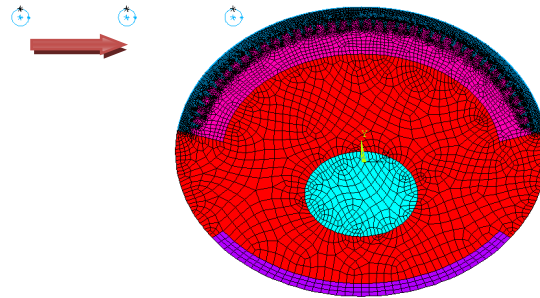


Figure 10. Simulation procedure for one-finger case

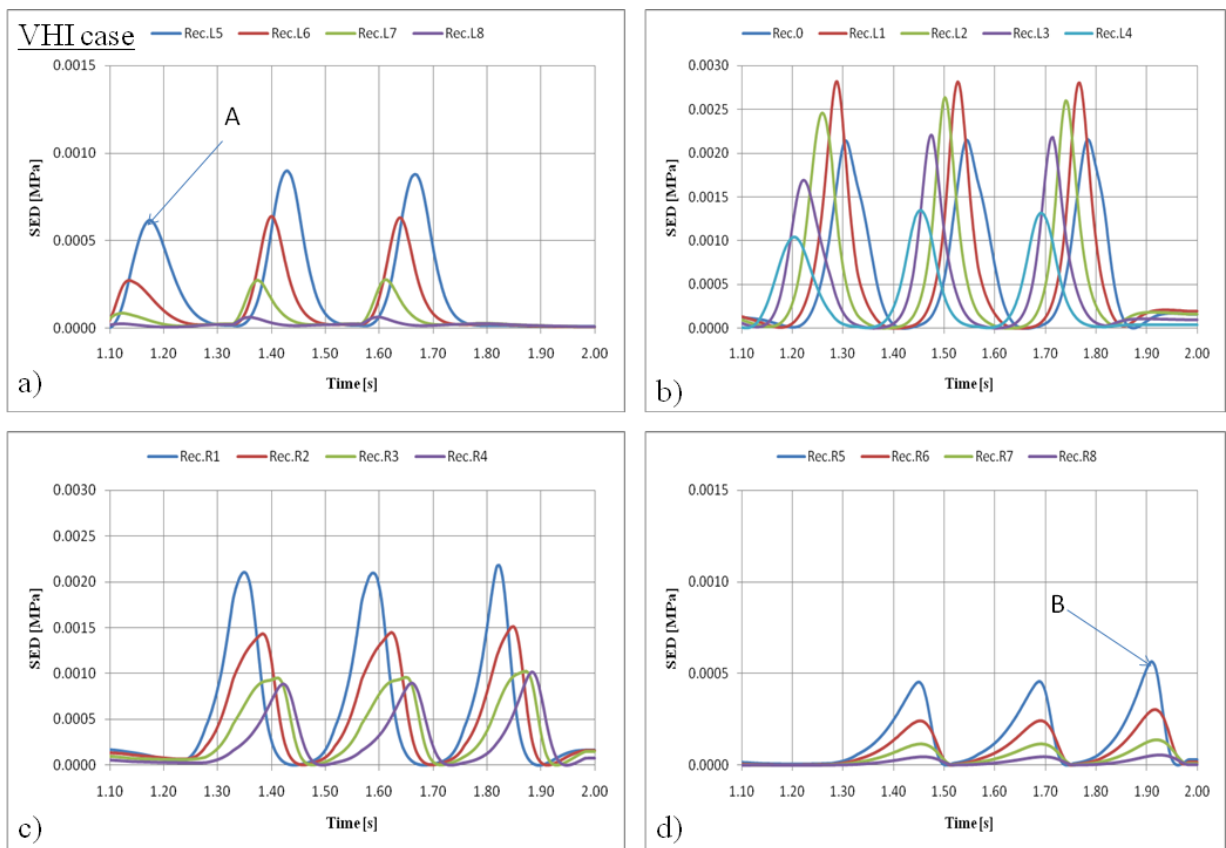


Figure 11. Time variation in SED for VHI case

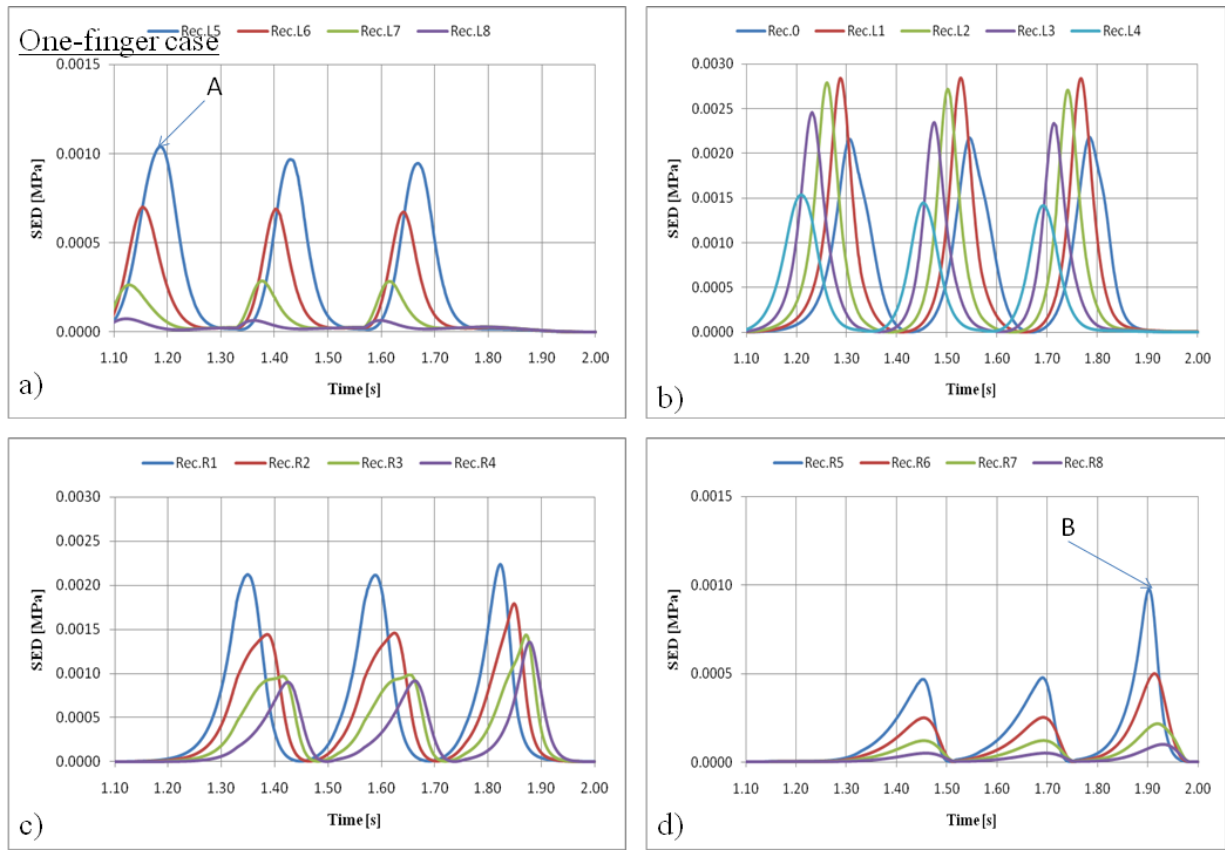


Figure 12. Time variation in SED for one-finger case

c. Simulated result

As explained before and shown in Fig. 9, since the wires contact the finger model from the left side, deform it, and leave the contact area, the left side receptors are stimulated first. The SEDs collected from the elements at the locations of the SAI receptors are shown in Figs. 11 and 12, which show the time variations in SEDs for the VHI and one-finger cases, respectively. The results start with the receptors stimulated first on the left side, Rec.L8~Rec.L5, and end with the receptors stimulated last on the right side, Rec.R5~Rec.R8.

Despite the small amount of compression (0.5 mm), notice the considerable difference in the response of the receptors between both cases. In general, for the VHI case the response of the SAI receptor to the traveling wires is smaller than that for the one-finger case. The peak values of Rec.L5 and Rec.R5 (point A in Figs. 11 and 12) show especially large differences. At points A, the response from the first wire for the VHI case is almost half of that for the one-finger case. For

the wires leaving the contact area, the response shown by point B is about half for the VHI case as well.

The response of the SA I receptor actually plays a role in VHI perception because the difference between the one-finger and VHI cases is distributed pressure. Although the feeling of touching a wire is required to induce VHI, the feeling decreases in the VHI case based on the present calculated results.

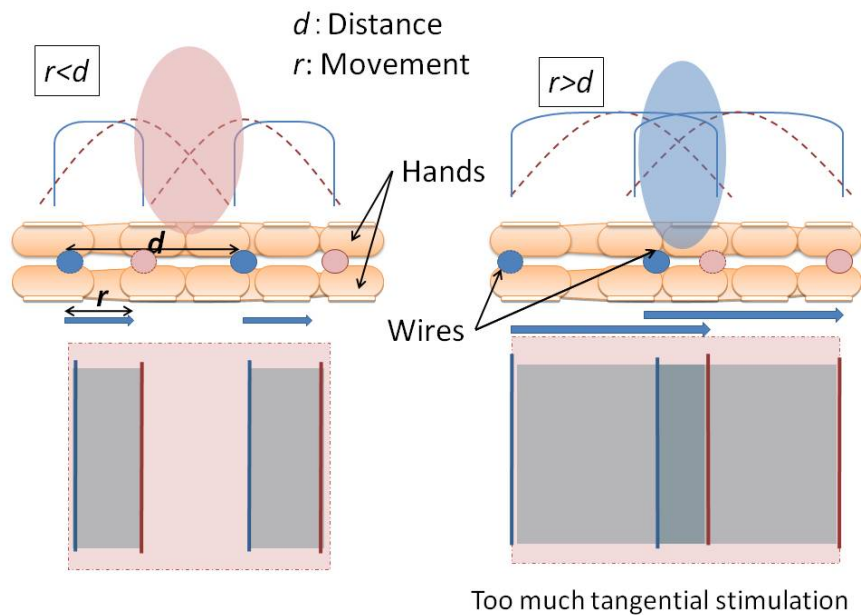


Figure 13. Variation in interval scale under passive touch

V. DISCUSSION

a. Mechanism of VHI

We assume that the plane feeling is caused by a constant pressure sensation, which seems reasonable because we feel pressure, for example, if we press a hand against a wall. The smooth and comfortable feeling is probably caused by the combined edge movement of the wire and the pressure sensation.

Next, we introduce a model of the VHI mechanism from the active touch results. In Fig. 13, the left side shows the ordinary case in which hand movement is within the distance between the two

wires. Tangential stimulation is applied to the hands within the gray square areas. The central area accepts both normal and tangential forces. In this area, subjects experience VHI.

However, the right side of Fig. 13 shows the case in which the distance is smaller than the hand movement and corresponds to the narrow distance case. In this case, the tangential stimulating area overlaps, as shown on the right side of Fig. 13. The subjects belonging to Group I in active touch seemed to judge this overlapping area as VHI in the previous psychophysical experiment. The large difference in the VHI proportion found between Groups I and II for 35-mm wire spacing seems to be caused by the active touch decided by each subject. If hand movement is controlled, the difference is diminished.

On the other hand, we cannot find any human subject belonging to Group I in the passive touch test. This result shows that the VHI sensation is controllable with wire spacing and can be reproduced more easily in tactile displays. VHI strength seems proportional to the size of the virtual film with a zero coefficient of friction.

The present model (Fig. 13) is supported by the simulated results of the present FEM analysis. Although both compressive force and wire movement are required to generate VHI, excessive time derivative of SED prevents VHI from being felt.

b. Abilities of Actuator for VHI-Based Tactile Display

Finally, we discuss the abilities of an actuator for a VHI-based tactile display. First, both tangential and normal stimuli are required, as discussed in the previous section. Although an array composed of three-dimensional actuators is not always needed, we require the combination of a two-dimensional actuator that generates shearing force and an actuator array that generates pressure distribution. Such tactile displays effectively generate VHI because it is very stable in passive touch.

VI. CONCLUSION

The strength of the velvet hand illusion (VHI) depends on the distance between two adjacent wires. VHI, which is caused by passive touch, is considerably stronger than that caused by active touch. This result suggests that VHI is controlled by mechanical external stimulation using tactile displays. In this paper, the mechanism of VHI is considered as follows: although the area bounded by two wires moves relative to the hands, tangential force does not occur on the hand

surface except for the wire-passing portion, causing operators to experience the illusion of touching a smooth virtual film with a zero coefficient of friction. Since VHI becomes weaker for a small distance between two adjacent wires, excessive tangential stimulation prevents VHI. Therefore, VHI control requires two actuations: normal actuation on the operator's finger surface to generate a touch feeling, and appropriate tangential actuation to generate a moving-edge feeling on the operator's finger surface. Our VHI model is supported by the present calculated FEM analysis results.

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